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Differences and Commonness between Submarine and Spacecraft Life Support Systems

Willigert Raatschen, Lutz Schauer

Astrium GmbH, Dept. TO51, 88039 Friedrichshafen, Germany

Francis Mesnage

DCNS, Warship Engineering, 50104 Cherbourg-Octeville, France

1 Abstract

Astrium has over 35 years experience in manned spaceflight as the prime contractor for the life support systems for Spacelab, the three MPLMs, the ATV and the Columbus module. Furthermore, Astrium has over 25 years experience developing submarine life support systems, which has included support to the major German shipyards with CO_2 removal and contamination control systems on conventional submarines. Astrium's experience will now be used for the development of the life support system for the new French nuclear attack submarines of Barracuda class.

DCNS is France's major shipyard for surface warships and nuclear as well as conventional submarines with a history well beyond the last century.

Working both spaceflight and submarine life support arenas it became obvious that there are many common requirements. However, there are also significant differences between spacecraft and submarine environments, which do not permit the application of some technologies to both platforms. This paper describes the differences in requirements between spacecraft and submarines (conventional and nuclear). The technical details will be addressed in this paper along with the commercial aspects of developing life support system for these unique environments.

2 Introduction

Spacecraft and submarines are more or less the only habitats with a completely isolated atmosphere environment. Even NBC shelters in which people shall be protected from outdoor toxic agents are not completely isolated while supplying outside air to the indoor environment and clean it by sophisticated filter technique. Gen labs are designed to protect the outdoor environment by enhanced filter methods from toxic agents or bacteria, present in the lab and thus, are neither completely isolated.

In spacecraft and submarines healthy and young to middle aged men and sometimes women live and work. Although the requirements of the work environment do not differentiate a lot (because metabolic cycles and indoor comfort requirements of astronauts and submariners are pretty much the same), differences are in the exterior environment, the mission durations and the resupply means and costs. The availability of electrical energy and the necessity to discharge heat is another constraint in the optimum selection of processes and applicable technologies.

Exterior Environment

For spacecraft the exterior environment is normally high vacuum (10^{-5} - 10^{-10} Pa), there is high vacuum on the moon and it may only rise to ~ 9 Pa on planet Mars.

The shell of a spacecraft needs to be protected against meteorites and space debris. The discharge of heat is normally done by radiators. Due to sun radiation onto one side and heat

emission into deep space on the opposed side the interior wall surfaces' temperatures can vary substantially. Cold surfaces could face condensation problems with the risk of mould growth and formation of micro organisms. Electrical shell heaters are applied to avoid condensation. Other designs ventilate the interior surface of the modules' walls to keep them warm. The harsh radiation environment impacts the shell design but has only a minor impact on the life support design. When designing air-looks for space walks on a planet, special focus needs the avoidance of dust intake.

Submarines' environment is deep sea with temperatures running from 32℃ in tropical areas to slightly -2℃ in salt water and water pressure increases of roughly 10 bar per 100m diving depth.

Usually the interior surfaces of the shell are not insulated, therefore condensation occurs. This can increase the risk of micro organisms; it causes accumulation of water in bilges with the risk of fouling processes and contaminant emissions.

Mission Durations

In space current manned missions usually range between 7 and 180 days. Subsea missions range from less than one day to 90 days per mission.

For short missions of a spacecraft or a submarine the required volume of the life support system is a major design driver, for space the required system mass is even more important, as upload costs increase with mass.

As regenerative life support systems usually built larger, do not require spacious consumables and request more energy, usually non-regenerative technologies are better suited for short missions both in space and in subsea. Depending on the mission profile, availability of resources and system and logistic costs constraints there is a break-even at which regenerative technologies trade better. On short missions simple systems can be adequate or even omitted which are necessary for long term missions, e. g. monitoring of air quality.

Whereas the longest submarine mission is 90 days, before it surfaces again and flushes the indoor air with fresh outdoor air, the International Space Station (ISS) is manned since 2001 and its contractual operation is till 2015 with good chance of prolongation till 2020, its air will not be flushed and renewed. Therefore the purification of the air needs more attention on ISS than on a submarine. Thus both indoor environments need to be healthy enough to maintain the crew in good shape.

Re-supply means and costs

Submarines are designed for life times of ±30 years. A manned space capsule may only be used one or twice. The more missions are undertaken the higher usually the impact of costs of consumables is. As a matter of fact non-regenerative systems create higher consumable costs than regenerative systems.

Electrical Energy

Electrical energy is a very limited resource on all spacecrafts but also on non-nuclear submarines. Some technologies can simply not be selected due to the lack of energy. An example of today is regenerative CO_2 removal systems not installed on most conventional submarine.

3 Requirements for Short and Long Duration Spaceflight and Diving Missons

The following abbreviations are introduced: C-sub for a conventional submarine and N-sub for a nuclear-powered submarine.

3.1 Environmental Conditions

Often environmental conditions are defined for nominal operation and exceptional operation. The latter is usually defined for 1-2% max. of the mission duration, during which problems (no electricity, repairs, accidents etc.) might occur. Figure 3-1 shows the environmental conditions for the ISS and Figure 3-2 shows them for a French N-sub. Without going into detail submarine environmental conditions usually span a much wider range than for a spacecraft. This means that the technology applied to a submarine must cope with a broader range of inlet conditions. This could have substantial influence on the design of the air conditioning system, on the adsorptivity of the CO_2 removal resin or the activated charcoal beds.

The influence of indoor pressure is not that big. Table 3-1 shows data for ISS and average requirements for N-subs.

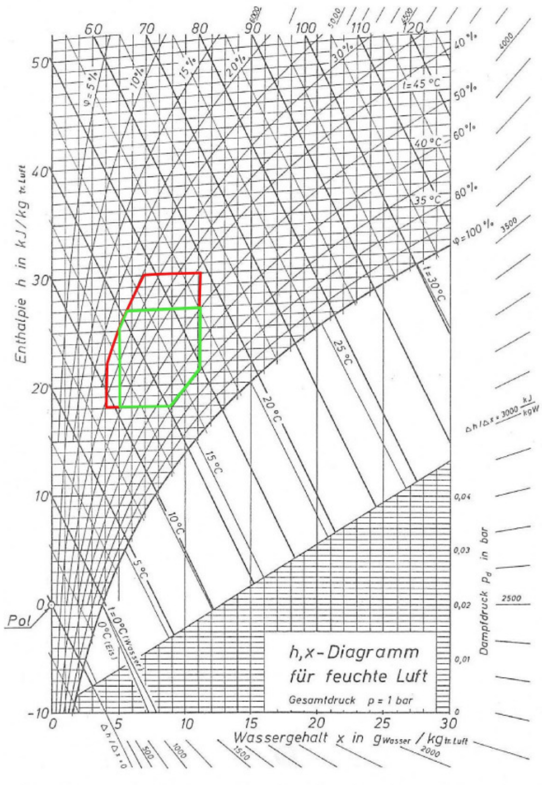

Figure 3-1: Nominal (green) and exceptional (red) environment of the ISS

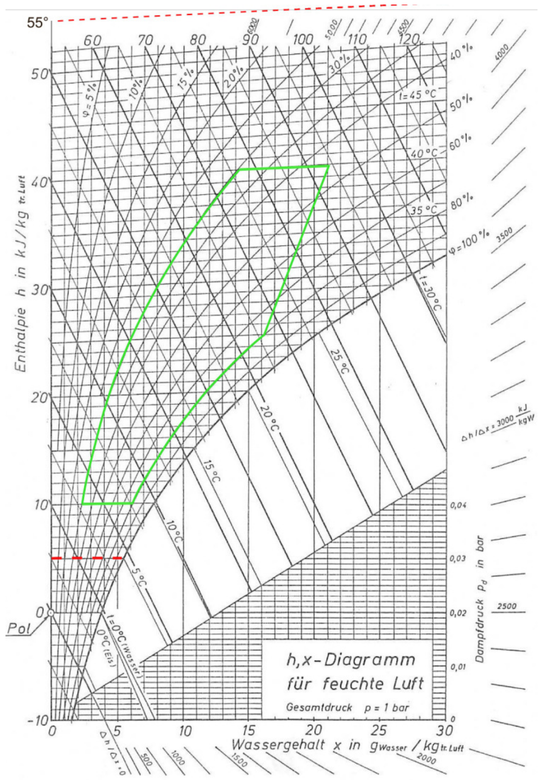

Figure 3-2: Nominal (green) and exceptional (red) environment of a French N-sub

	nominal		Exceptional	
	min. [kPa]	max. [kPa]	min. [kPa]	max. [kPa]
ISS	95,8	102,7		
submarine	90	110	80	130

Table 3-1: Cabin pressures requirements on ISS and in submarines

Overpressure in a spacecraft is critical due to structural limits. Therefore overpressure relief valves avoid such situations e. g. after a leak or a fire onboard. Overpressure in a submarine up to 5 bar usually does not cause problems.

Underpressures in both spacecraft and subs are critical because the minimum needed oxygen partial pressure decreases, which causes a direct health risk to the crew. On the ISS oxygen masks are distributed all over the modules to cope with such a situation.

3.2 Atmosphere composition

To come to a lighter design former spacecrafts like Apollo, Mercury, Gemini and Skylab tried to maintain the cabin pressure at 34,5 kPa while keeping the O_2 concentration between 70vol% and 100vol% **[1]**. The space shuttle, the ISS and the Soyuz capsules are designed for 1 bar atmospheric pressure, while maintaining partial pressures according to Table 3-2. However, new designs for spacecraft as the currently designed Crew Exploration Vehicle (CEV) of NASA shall operate again at lower atmospheric pressure.

3.3 Ventilation and De-Humidification

Ventilation in space is not a matter of comfort, it is a matter of survival. No ventilation in a zero-g environment will cause a repeated intake of exhaled air with subsequent suffocation. The second threat is the missing cooling function by buoyancy of the air with an increase of temperature. The ventilation requirements on ISS and subs are depicted in Table 3-3.

	ppO_2 [kPa] nominal		ppN_2 [kPa]	ppO_2 [kPa] exceptional		$ppCO_2$ [kPa] nominal	
	min	max		min	max	min	max
ISS	19,5	23,1	<80		24,8	<0,7	1,0
Subs	20	20,5	≈80	19	<23	≤0,5	0,7

Table 3-2: Cabin atmosphere composition on ISS and submarines

	Air velocity in habitat area 67% [m/s]		Air velocity everywhere [m/s]	
	min	max	min	max
ISS	0,076	0,203	0,036	1,016
Sub	1	2	1	2

Table 3-3: Air velocity requirements on ISS and in French N-subs

The maximum air velocities are derived from human comfort criteria, the minimum values from crew health safety aspects.

Air velocities on submarines are higher, the revitalized air supply flows to the different rooms are determined on the basis of 25 m^3/(pers. h).

3.4 Air Revitalization

Air revitalization summarizes the functions oxygen generation, CO_2 removal and CO_2 reduction. Design values for Oxygen generation rates and CO_2 removal rates on spacecraft and subs do not differ a lot. Table 3-4 shows an overview.

	O_2 consumption rate [kg/pers d] ([Nl/pers h])	CO_2 removal rates [kg/pers d] ([Nl/pers h])
ISS design values	[0,84-0,86]	[1,0] (21,2)
ISS 8 year average	[0,85] (24,8)	[1,0] (21,2)
Subs	[0,85] (24,8)	[0,94] (20)

Table 3-4: Design and measured values of oxygen consumption and CO_2 removal rates

In space desorbed CO_2 can easily be vented overboard. In subs the CO_2 must be pressurized for overboard discharge. CO_2 especially at high pressures and low temperatures immediately dissolve in sea water. Normally no CO_2 bubbles enter the surface.

On conventional subs oxygen is usually supplied from pressurized O_2 cylinders, some fuel cell driven subs use the boil-off oxygen from liquefied oxygen both for breathing and for fuel cell operation.

N-subs and also the ISS use water electrolysis to produce O_2. This process at the same time also produces hydrogen, H_2. The motivation to avoid H_2 overboard discharge on the ISS and on subs is different. In space one wants to close process loops to the furthest extent to save upload mass. A submarine doesn't like to be spotted. For subs this is sometimes a problem because H_2 dissolves very poorly in sea water and H_2 bubbles are likely to be spotted on the surface or detected by sonar.

Table 3-2 also states the maximum CO_2 concentrations. In submarines there is a clear trend during the past 10 years to improve cabin air quality by reducing the mean cabin CO_2 concentration from levels of 0,7-1,0 vol.% down to 0,5 vol.%.

3.5 Trace Contaminant Control System (TCCS)

Trace contaminants on the ISS are to 80% products caused by the human metabolism. The remaining 20% are from material off-gassing, from leakage or improper handling of processes. Starting from the early NASA Apollo missions in the 60ies to 8 years of air constituent monitoring on the ISS it is amazing to see, that today's contaminant load models (see Table 3-5) lead to an active contaminant control equipment design with a minimum of 10% design margin. This leads to optimum TCCS mass and minimum consumables.

Although contaminant load models for submarines exist, however they currently don't seem to have the quality which has been achieved for spacecraft.

Conventional submarines with their moderate diving times usually use only activated charcoal which is replaced after 20-30 days of diving and snorkeling periods. Future air independent propulsion (AIP) submarines will need to put more effort on trace contaminant control. N-subs' TCC systems are more advanced. Due to longer missions, cooking processes onboard, with sometimes permission of smoking not only adsorption but also catalytic processes are applied.

CONTAMINANT	SMAC (mg/m^3)	RATE	
		EQUIPMENT (mg/kg-d)	METABOLIC (mg/person-d)
Methanol	90	1.3×10^{-3}	0.9
Ethanol	2,000	7.8×10^{-3}	4.3
n-butanol	40	4.7×10^{-3}	0.5
Methanal	0.12	4.4×10^{-6}	0.4
Ethanal	4	1.1×10^{-4}	0.6
Benzene	0.2	2.5×10^{-5}	2.2
Methylbenzene	15	2×10^{-3}	0.6
Dimethylbenzenes	37	3.7×10^{-3}	0.2
Furan	0.07	1.8×10^{-6}	0.3
Dichloromethane	10	2.2×10^{-3}	0.09
2-propanone	52	3.6×10^{-3}	19
Trimethylsilanol	4	1.7×10^{-4}	0
Hexamethylcyclotrisiloxane	9	1.7×10^{-4}	0
Ammonia	2	8.5×10^{-5}	50
Carbon monoxide	17	2×10^{-3}	18
Hydrogen	340	5.9×10^{-6}	42
Methane	3,800	6.4×10^{-4}	329

SMAC = 180-day exposure

Table 3-5: Load model for spacecraft TCC design acc. to [2]

Usually the threshold values for a contaminant do not differ so much; it is more the contaminant cocktail which makes the difference. A diesel driven conventional sub could have Diesel exhaust gas products in the air what a N-sub usually not has. Product gases from Torpedo firing are usually not expected on a spacecraft. Processes onboard which might leak such as HVAC compressors need to be reflected.

After a fire the ISS needs to recover from it. The TCCS must be capable to eliminate emitted gases while a sub could surface and flush the cabins with outdoor air.

3.6 Air Constituents Monitoring

It is necessary to monitor O_2, CO and CO_2, in case of onboard batteries and water electrolysis also H_2. Some navies also monitor CH_4. Continuous air quality monitoring of VOCs is not yet state-of-the-art not in C-subs nor in N-subs. Sometimes the refrigerants (R134a, R12, R404, R114) and H_2S (in nuclear subs) are continuously monitored.

The Space Shuttle monitors O_2, CO_2 and H_2, whereas on ISS O_2, N_2, CO_2, H_2 and CH_4 are analyzed. A multi constituent analyzer continuously measures VOC.

3.7 Water Supply and Regeneration

In space water is one of the very scare resources onboard. Figure 3-3 schematically shows the water and oxygen loop and Table 3-6 depicts the water balance on the ISS.

Water requirements (liters/person day)		**Water sources (liter/person day)**	
Drinking	2.1l	Condensate	1.5l
H_2O in food	0.5l	Urine processing	1.44l
Hygiene	0.5l	Sabatier reactor	0.45l
Toilet flushing	0.3l	H_2O in food	0.5l
Oxygen Generation	0.95l	Moisture loss	0.16l
Total	**4.05l**		**4.05l**

Table 3-6: Daily water requirements and supply for one astronaut

If one subtracts from the daily water need of one astronaut of 4,05l 1l for oxygen generation by electrolysis, 50% of the consumed water (1,5l) can be reused by recycling of humidity condensate. Another 39% (1,14l) could be reused having a urine processor onboard.

On a sub the water consumption per crew member is significantly higher. There is no water recycling on C-subs. Potable water is carried in tanks. Toilet flush is often done with sea water. N-subs use reverse osmosis to make-up sea water to technical or potable water.

On a nuclear French submarine the water consumption is shown in Figure 3-4.

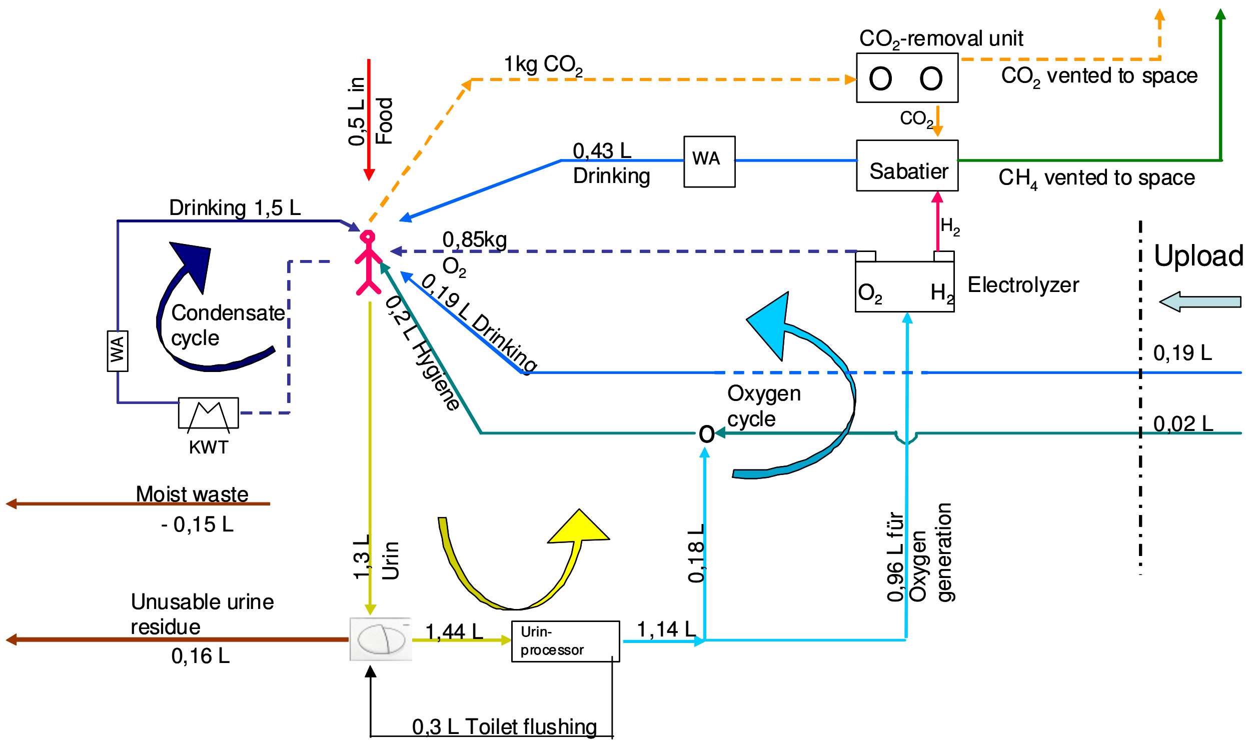

Figure 3-3: Closing the water and oxygen cycle on the ISS **[3]**, numbers are liters per crewmember and day

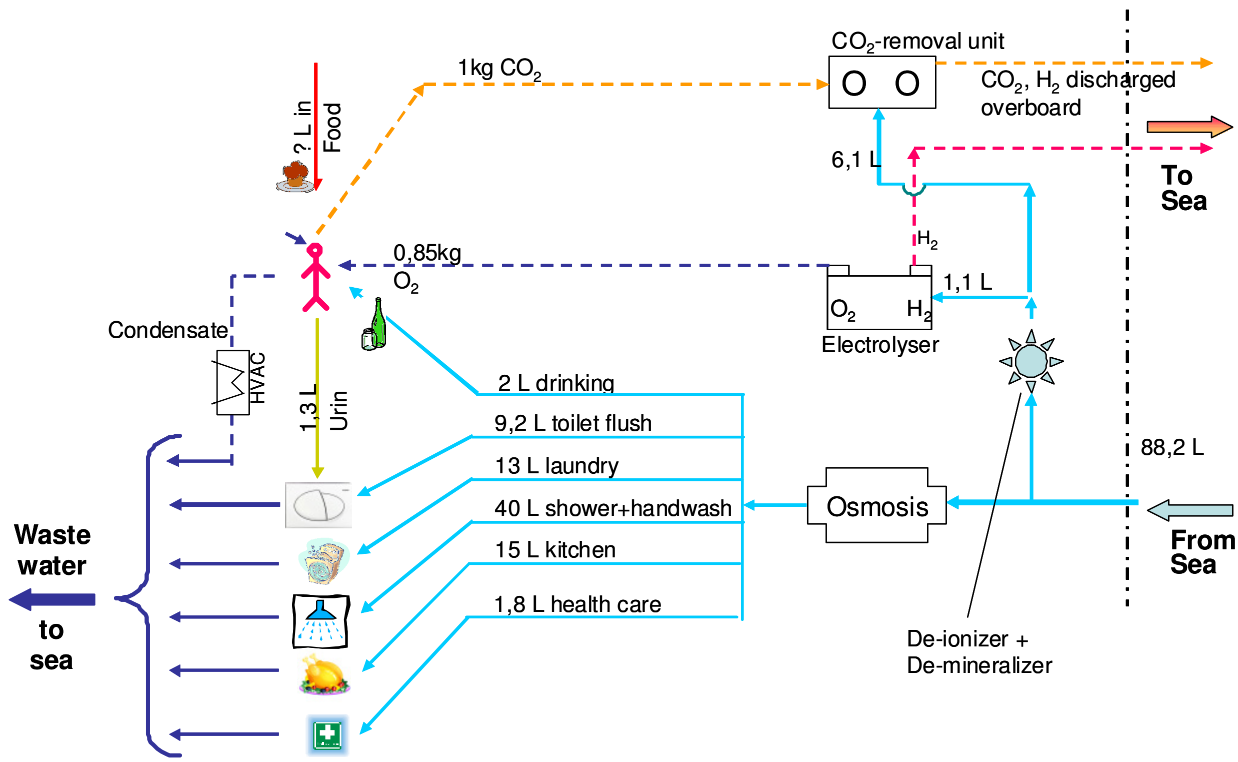

Figure 3-4: Water make-up and consumption flows on a French N-sub, numbers are liters per crew-member and day

Via osmosis in total 88,2 l of water per day and crewmember are made-up of sea water. Out of this amount 7,2 l are de-ionized and demineralized to feed the oxygen generation and contamination control plant.

2 liters are for drinking, 15 l for food preparation in the kitchen, 13 l for the laundry, 40 l for shower and hygiene, 9,2 l for toilet flush and 1,8 l for health.

3.8 Waste

Waste consists of urine, feces (grey and black water) and trash. On ISS water from urine is recovered. Feces and other trash are stored in plastic bags and discharged on station departing vehicles (ATV, progress) to be later burned during re-entry in the atmosphere. Hygiene waste water and condensate is regenerated.

In submarines, wastewater and biodegradable waste are discarded back to the sea. The not biodegradable waste is compacted and stored in cold rooms.

3.9 Emergency Systems

As a back-up of system mal functions or loss of power passive systems are preferred. On spacecraft and subs there is usually a back-up for O_2 supply and CO_2 removal.

4 Technology Trade-Offs

Due to the different environments and mission objectives the evaluation of technologies for spacecraft and subs can differ. Table 4-1 shows the major criteria which need to be reflected during a technology selection and trade-off process. The next chapters provide examples why certain technologies work / not work for different applications.

4.1 Oxygen supply

Oxygen provision can be done from pressurized O_2 cylinders, from oxygen candles, through evaporation of liquid oxygen or via water electrolysis.

A process using potassium super oxide KO_2 is also known which absorbs the CO_2 from the cabin while producing oxygen at the same time. It is not known, if this process has ever been realized in space or in subs as it is difficult to control.

O_2 cylinders

They are common in space and in subs either as nominal O_2 supply mean or only for emergency situations.

O_2 candles

Are to a far extend only used as a back-up O_2 supply system. However, there are C-Subs still operating with O_2-candles for regular O_2 production.

Liquid O_2 (LOX)

LOX is neither common in space nor in N-Subs. However, C-subs with H_2/O_2 fuel cells use LOX as oxidizer for propulsion and for breathable oxygen.

Water Electrolysis

Water electrolysis is only favorable for long missions and consumes a lot of energy. Therefore it won't be applied during short spaceflights or on C-Subs. For N-Subs it is more favorable to use a high pressure electrolyser to avoid a H_2 compressor for overboard discharge, whereas in space a low pressure electrolyser would be o.k.

	Spacecraft		**sub**	
	Short	Long	Con-vent.	nu-clear
volume	+	+	+	+
mass	+	+	+	+
energy	+	+	+	-
crew time	+	+	+	+
reliability	+	+	o	+
re-supply	-	+	o	o
signature-noise,	o	+	o	+
signature-bubbles	-	-	o	+
closed-loop processes	-	+	-	o

Table 4-1: Selection criteria and their importance of the different applications (+=important; -=not important; o=ambivalent)

In case of a mole sieve CO_2 removal system as on ISS, where desorption is done by a sub-ambient pressure swing process a compressor is needed to bring the CO_2 flow pressure up to Sabatier operating pressure (~ 0,9 bar).

4.2 CO_2-Removal

Non-regenerative means to absorb CO_2 are Soda Lime and Lithium Hydroxide (LiOH). Regenerative techniques are temperature / pressure swing adsorption / desorption via mol sieve, solid amine ion exchange resin with steam desorption (ASTRINE™ system) and liquid amine systems (MEA). The freeze out of CO_2 is another technology but not yet mature to be applied.

In space MEA systems are not favorable due to continuous emissions of small amounts of monoethanolamine into the air and it would require extensive liquid / gas separations which is difficult in a ZERO-g environment.

Mol sieve with prior air de-humidification is currently used on the ISS and the ASTRINE™ system is in the development process to be operated on ISS.

LiOH cartridges are used as back-up systems and favored instead of soda lime due to its higher capacity and its potential to achieve lower (<0,5 vol%) onboard CO_2 concentrations.

On C-Subs soda lime is very common because of its low price. Required CO_2 mean concentrations onboard are usually above 0,7 vol%. In C-Subs where 0,5 vol% of CO_2 is required, normally LiOH is used.

Mol sieve systems are only in operation in N-Subs due to the high consumption of electrical energy. Solid and liquid amine systems have the potential also to be used on C-Subs because a considerable amount of thermal energy is needed and could be used from other waste heat processes. A good heat source is an Air Independent Propulsion (AIP) C-Sub with a Closed-Cycle Diesel engine or a Fuel Cell powered C-Sub with a reformer.

4.3 CO_2 - Reduction

There are two processes available to avoid hydrogen emissions. One process which is applied in space is shown in Figure 4-1.

The H_2 of the electrolysis process reacts with the removed concentrated CO_2 to methane and water. While the methane can't be further used in space and is vented overboard, the water is a very valuable source. Thus the Sabatier process closes the oxygen loop. The volumetric amount of methane to be discharged overboard is approx. 25% of the H_2 flow.

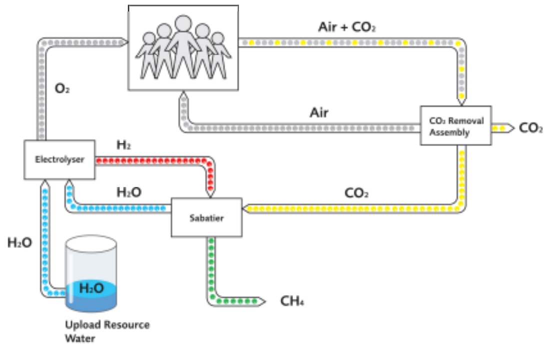

Figure 4-1: CO_2 reduction using the Sabatier process

The Sabatier process requires no additional energy, high pressure electrolysis or H_2 compressor. The process pressure is slightly below ambient to eliminate H_2 leakage. Thus the desorbed CO_2 needs to be at approx. ambient pressure. When using the Astrium ARES process, where ASTRINE™, an ion exchange resin is used for CO_2 absorption and steam of 105°C is applied for desorption, no additional vacuum pump or compressor is needed for make-up of the CO_2 to route it to the Sabatier reactor.

Methane has twice the solubility in water than H_2. Methane is a natural gas and everywhere in the ocean methane bubbles enter the surface. Thus if the Sabatier process is applied on a submarine it avoids H_2 discharge and only dumps small amounts of methane together with the excess CO_2 overboard. If a methane pyrolysis process is followed, the H_2 bound to the methane could be back-routed to the Sabatier reactor the convert 100% of the CO_2 and fully close the oxygen and hydrogen loop.

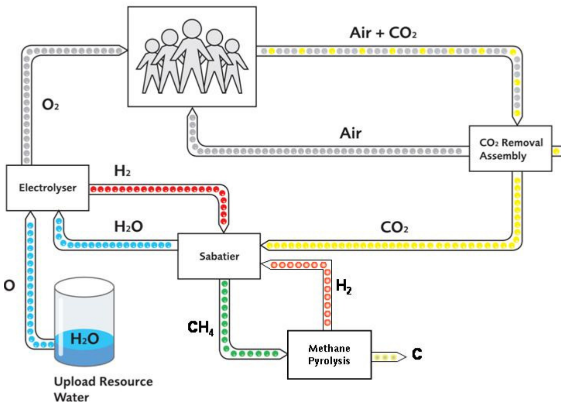

Figure 4-2: CO_2 reduction with Sabatier and CH_4 pyrolysis

The second way to avoid H_2 leaving the system is the methanol process.

4.4 Trace Contaminant Control (TCC)

H_2, CO, CH_4

Hydrogen (H_2) as a product from battery charging processes or electrolyser leakage, CO emissions from cooking processes and crew as well as methane (CH_4) as a metabolic product need to be eliminated. In space and on submarines catalytic reactions are used to burn these gases into CO_2 and water. Depending on the catalyst material catalyst temperatures range between 150°-350°C. The processes in space and in subsea are comparable.

VOC

Applied techniques are physical and chemical adsorption by activated or coated charcoal, and catalytic reaction to CO_2 and H_2O. Also for VOC removal there are no major differences between space and subsea. In space there is a strong effort to regeneratively remove VOC to avoid upload mass of consumables and to come to more compact designs.

Refrigerants

In subs the HVAC compressor often has small leaks, which build-up in the cabin atmosphere. Commonly used refrigerants on subs are R134a, R12, R404, R114. They all adsorb very poorly on charcoal, some can be removed in small amounts on a mole sieve process or they can be decomposed at high temperatures > 300°C. Care must be taken that all toxic decomposition products are completely removed.

In space it is the radiator cooling loop which either contains ammonia (NH_3) or a Freon. NH_3 is removed by a chemically treated absorbent while no means currently exist to eliminate Freons. Some molecules might be decomposed at the high temperature catalyst, but a R218 leakage event of 24. September 2007 on ISS showed that the refrigerant removal mainly took place by the air dilution processes of visiting vehicles like the Space Shuttle, Progress and Soyus flights.

4.5 Water Regeneration

On ISS condensate loaded with VOC is regenerated by a multifiltration process with catalytic oxidation. Hygiene water and pretreated urine is regenerated by vacuum vapor distillation. The regeneration efficiency is ~ 100% for condensate and ~85% for hygiene water and urine.

On C-Subs or French N-subs there is no waste water regeneration.

4.6 Air constituents Monitoring

Despite many technical difficulties the ISS has a humidity, O_2 and CO_2 sensor in each module. There is a centralized Major Constituents Analyser (MCA), a mass spectrometer to collect air samples once a minute from each module to be analyzed for O_2, N_2, CO_2, H_2 and CH_4.

On C-Subs continuous monitoring of VOC is usually not done. Some navies collect grab samples (bags or adsorption tubes) which are analyzed later in a laboratory. Continuous VOC monitoring is also not state-of-the-art on N-Subs.

5 Conclusions

Spacecraft and submarines have a lot in common regarding requirements and applied technologies for life support. C-Subs life support systems cover the basic life support functions like O_2 supply and CO_2 removal while using mainly non-regenerative techniques comparable to short duration mission spacecrafts. The lack of electrical energy is the major reason for C-Subs that regenerative means can't be installed.

The efforts undertaken in space to understand, predict, and quantify emissions is much higher than in the submarine domain. Contamination control devices in spacecraft are better optimized (less volume, less consumables, less crew time based on a comprehensive understanding of sinks and source rates) and therefore more effective.

Therefore it is worth while for naval life support design to learn from space.

To discharge gaseous or liquid waste products on submarines high pressures (20 - 60 bar) are needed, whereas in space the products are just vented into space or need to be stored.

Due to the non-existing gravity in space life support hardware is by far more complex, especially if buoyancy effects, which can be used on ground, need to be replaced by other means and when phase separation is needed.

To discharge water, H_2 and CO_2 pumps and compressors are needed on submarines. High pressure water electrolysis is favorable on N-subs for H_2 discharge without compressor.

In order to avoid high pressure electrolysis and to close the oxygen loop on a submarine the Sabatier process as developed for space could be applied as well.

6 References

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